

# A scenario of the formation of isolated X-ray pulsars with anomalously long period

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**Abstract.** A scenario of the formation of isolated X-ray pulsars is discussed with an application to one of the best studied objects of this class 1E 161348-5055. This moderately luminous,  $10^{33} - 10^{35} \text{ erg s}^{-1}$ , pulsar with a relatively soft spectrum,  $kT \sim 0.6 - 0.8 \text{ keV}$ , is associated with an isolated neutron star, which is located near the center of the young ( $\sim 2000 \text{ yr}$ ) compact supernova remnant RCW 103 and rotates steadily ( $|\dot{\nu}| \leq 2.6 \times 10^{-18} \text{ Hz s}^{-1}$ ) with the period of 6.7 hr. We show that in the current epoch the neutron star is in the accretor state. The parameters of the source emission can be explained in terms of the magnetic-levitation accretion scenario in which the star with the surface magnetic field of  $10^{12} \text{ G}$  accretes material onto its surface from a non-Keplerian magnetic fossil disk at the rate  $10^{14} \text{ g s}^{-1}$ . A neutron star could evolve to this state in a High-Mass X-ray Binary (HMXB), which had disintegrated during the supernova explosion powered by the core-collapse of its massive component. The life-time of an isolated X-ray pulsar formed this way can be as long as a few thousand years.

**Keywords:** Accretion and accretion disks, X-ray binaries, neutron star, pulsars, magnetic field

**PACS:** 97.10.Gz, 97.80.Jp, 95.30.Qd

## 1. INTRODUCTION

Isolated X-ray pulsars constitute a subclass of isolated neutron stars (i.e. not associated with a close binary system) displaying regular pulsations in their X-ray emission. This subclass now includes more than 70 objects. Among them are radio-pulsars emitting also X-rays (see [1] and references therein), anomalous X-ray pulsars and soft gamma-ray repeaters (see [2] and references therein), compact X-ray sources in supernova remnants [3], and isolated neutron stars of a relatively low luminosity, known under a romantic name “The Magnificent Seven” [4]. A great diversity in observational manifestations of these stars reflects differences in mechanisms responsible for generation of their X-ray emission. Nevertheless, assignment of these objects to a single sub-class is justified by a similarity of their rotational evolution. The average spin period of these stars,  $P_s$ , is monotonously increasing,  $\dot{P} > 0$ , and their spin-down ages,  $\tau \sim P_s/2\dot{P}$ , are mostly in the range  $10^3 - 10^5 \text{ yr}$  (see [5] and references therein).

The most simple explanation of the observed spin evolution of isolated X-ray pulsars is presented by the canonical model of a radio-pulsar in which the spin-down

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power of the star is described by the magneto-dipole formula,  $L_{\text{md}} = f_m \mu^2 \omega_s^4 / c^3$ , where  $\omega_s = 1/P_s$  is the angular velocity and  $\mu = (1/2) B_* R_{\text{ns}}^3$  is the dipole magnetic moment of the neutron star of radius  $R_{\text{ns}}$ , with the surface magnetic field  $B_*$ . The dimensionless parameter  $f_m$  ranges within  $1 \leq f_m \leq 4$  according to [6, 7]. In this approach, the isolated X-ray pulsars are described in terms of a young neutron star with strong magnetic field. A number of mechanisms of X-ray emission from these objects have been considered. Among them are current dissipation and particle acceleration in the pulsar magnetosphere, dissipation of the super-strong magnetic field in the neutron star crust, and heating of the stellar photosphere by the thermal energy coming from its hot core (cooling), which can proceed at a rather high rate during the early stage of stellar evolution [8].

It should be noted, however, that the radio-pulsar model is not an universal instrument for analysis of spin evolution of neutron stars. In particular, it can be applied only to those pulsars whose period satisfies the condition  $P_s < P_{\text{ej}}$ , where

$$P_{\text{ej}} \simeq 20 f_m^{1/4} \mu_{30}^{1/2} m^{-1/2} n^{-1/4} v_7^{1/2} \text{ s} \quad (1)$$

is a period at which the star switches its state from ejector (i.e., a spin-powered pulsar) to propeller [9]. Here  $\mu_{30} = \mu / 10^{30} \text{ G} \cdot \text{cm}^3$  and  $m$  is the neutron star mass,  $M_{\text{ns}}$ , in units of  $1.4 M_{\odot}$ .  $n$  is the gas density around the pulsar magnetosphere, and  $v_7$  is the relative velocity between the star and the surrounding material,  $v_{\text{rel}}$ , in units of  $10^7 \text{ cm/s}$ . Assuming, that the gas density around the star at the current stage of its evolution does not significantly deviate from the number density in the interstellar space (i.e. about one atom per cubic centimeter), we can see that the above-mentioned condition is satisfied for the majority of currently known isolated X-ray pulsars. The only exception is the X-ray pulsar 1E 161348-5055 (hereafter 1E 1613) with the period  $\sim 6.7 \text{ hr}$ . Analyzing the parameters of this pulsar in Section 2, we come to the conclusion that it is a neutron star in the accretor state (Section 3). Good agreement with observational data can be achieved in the scenario of magnetic-levitation accretion, in which a neutron star with magnetic field  $\sim 10^{12} \text{ G}$  accretes material onto its surface from a non-Keplerian magnetized residual disk. Magneto-rotational evolution of this star and the origin of its fossil disk are discussed in Section 4 under assumption that 1E 1613 is a descendant of a binary system. We show that the origin of this source can be explained within a canonical evolutionary model for a High-Mass X-ray Binary (HMXB), which had disintegrated after the supernova explosion caused by a core-collapse of its massive component. The pulsar 1E 1613 in this scenario is an old neutron star which had been born in the first supernova explosion and evolved as a part of a HMXB. Summarizing main conclusions of our research in Section 5, we estimate parameters of the binary systems which could be progenitors of the long-period isolated X-ray pulsars.

## 2. PARAMETERS OF 1E 161348-5055

The point-like X-ray source 1E 1613 was discovered in 1979 on board of the Einstein space mission through observations of the supernova remnant RCW 103 [10]. The source is located close to the center of the nebulosity, the distance to which is  $3.2 \pm 0.1 \text{ kpc}$  [11].

This nebula is not a typical remnant of SN II explosion. It is round-shaped, has a fibrous structure, low expansion velocity ( $\sim 1100$  km/c) and, for its age,  $\tau_0 \simeq 2000 \pm 1000$  yr, relatively small spatial dimensions  $\sim 7.7$  pc [12]. Nebulosities with such parameters constitute less than 20% of all known by now remnants of SN II, which probably exploded in a gaseous medium of enhanced density [13].

The first doubts concerning the assumption that the source 1E 1613 is a young cooling neutron star arose after spectral observations of the object with the space observatory ASCA [14]. Its X-ray emission was found to have a mean luminosity  $L_X \approx 10^{34}$  erg/s, and to contain a blackbody component of temperature  $kT \sim 0.6 - 0.8$  keV and emitting radius  $a_p \sim 600$  m, which is substantially smaller than the radius of the star itself [14, 15]. Moreover, analyzing the data on 1E 1613 from three space telescopes (Einstein, ASCA and ROSAT), Gotthelf et al. [15] have argued that the X-ray brightness of the source undergo slow variations with the amplitude reaching the order of magnitude, that is untypical for a cooling neutron star, but is an attribute of neutron stars accreting material onto their surface.

Brightness variations of 1E 1613 with the period  $\sim 6$  hr, suspected in Chandra observations of this source, stimulated the efforts in search for an optical counterpart to this object. Observations made with ESO VLT in the near infra-red allowed to set an upper limit to the luminosity of a hypothetical companion,  $L_{IR} \leq 4 \times 10^{31}$  erg/s, which could be only a star later than *M4* [3]. This result argued in favor of assertion that 1E 1613 is not a member of any binary system, i.e. it is an isolated neutron star emitting due to either accretion from a fossil disk or rapid dissipation of the super-strong magnetic field [16].

The period of pulsations,  $P_{\text{obs}} = 6.67 \pm 0.03$  hr, was measured through X-ray observations of 1E 1613 obtained with XMM-Newton [17]. Discussion on the evolutionary status of the pulsar inspired by this discovery resulted in a number of scenarios in which 1E 1613 was considered in terms of a neutron star with super-strong magnetic field ( $\geq 10^{15}$  G) which either accretes material from a residual Keplerian disk [17, 16], or is a member of a low-mass X-ray binary [18]. A hypothesis about 1E 1613 being a millisecond pulsar in a low-mass close binary system with the orbital period of 6.7 hr was discussed in [19].

High stability of the pulse period,  $|\dot{P}| \leq 1.6 \times 10^{-9}$  s/s (or, correspondingly,  $|\dot{\nu}| \leq 2.8 \times 10^{-18}$  Hz/s, where  $\nu = 1/P_s$  is the spin frequency), detected by Esposito et al. [20] through analysis of X-ray observations of 1E 1613 with Swift, Chandra and XMM-Newton, has opened a new era in the study of this exotic object. Examining their results, the authors of this discovery pointed out that the torque applied to the neutron star at the present time is significantly smaller than the value expected in all previously suggested models of this source. High stability of the pulsations shows that its spin period is now close to the equilibrium period whose value only slightly depends on variations of accretion rate from a residual disk. In the previous paper [21] we argued that such a situation could be realized in the scenario of magnetic-levitation accretion in which a neutron star with magnetic field  $\sim 10^{12}$  G accretes onto its surface from a residual non-Keplerian magnetized disk. Additional justification and further development of this approach is a subject of our investigation. Its results are presented in the following sections of this paper.

### 3. EVOLUTIONARY STATE OF 1E 1613

One of the key problems in the modeling of 1E 1613 is the current evolutionary state of this source. Studies of spin evolution of pulsars unambiguously indicate that the initial spin period of neutron stars at the time of birth,  $P_0$ , amounts to fractions of a second [22, 23]. If  $P_0 < P_{ej}$ , the star begins its evolution in the ejector state in which the spin period,  $P_s$ , grows according to the canonical model of radio-pulsars. During the phase when  $P_{ej} < P_s < P_{pr}$ , the rotational power of the star decreases through the propeller mechanism. Here  $P_{pr}$  determines the value at which the corotation radius of the neutron stars,  $r_{cor} = (GM_{ns}/\omega_s^2)^{1/3}$ , reaches its magnetosphere radius,  $r_m$ . If  $P_s \geq P_{pr}$ , the star is in the accretor state, in which evolution of its spin frequency is governed by the equation

$$2\pi I \dot{\nu} = K_{su} - K_{sd}. \quad (2)$$

Here  $I$  is the moment of inertia of the neutron star,  $\dot{\nu} = d\nu/dt$ , and  $K_{su}$  and  $K_{sd}$  are the spin-up and spin-down torques exerted on the star from the accretion flow. Hence, the neutron star can be observed in one of three states: ejector, propeller or accretor [24, 25, 26].

A possibility that 1E 1613 is presently in the ejector state can be excluded. The inequality  $P_{obs} < P_{ej}$  can be satisfied for the parameters of this source only if the surface magnetic field of the neutron star is in excess of  $10^{18}$  G. However, the existence of a neutron star with so strong magnetic field seems highly improbable (see [27] and references therein). Moreover, the expected spin-down rate of such an ejector,

$$\dot{\nu}_{ej} = \frac{L_{md}}{2\pi I \omega_s} = \frac{f_m \mu^2 \omega_s^3}{2\pi I c^3}, \quad (3)$$

exceeds the upper limit of the period derivative of 1E 1613, derived in [20], by two orders of magnitude.

An assumption that the star is in the propeller state means that its spin period satisfies the condition  $P_{ej} < P_s < P_{pr}$ , where (see Eq. 22 from [28]),

$$P_{pr} = P_{pr}^{(sp)} \simeq 10^3 \mu_{30}^{6/7} m^{-11/7} n^{-3/7} v_7^{9/7} \text{ s}. \quad (4)$$

A characteristic spin-down time of the star in this state is (see Eq. 21 from [28])

$$\tau_{pr}^{(sp)} \simeq 2 \times 10^{11} \mu_{30}^{-1} I_{45} m^{-1} n^{-1/2} \text{ yr}, \quad (5)$$

where  $I_{45} = I/10^{45} \text{ g cm}^2$ . Solving the system of equations (4) and (5) for  $\mu$ , we find that the spin period of the star in the propeller state could reach the value  $P_{pr}^{(sp)} \sim 6.7 \text{ hr}$  on a time span of  $\tau_{pr}^{(sp)} \sim 2000 \text{ yr}$ , only if  $\mu \geq \mu_{pr}$ , where

$$\mu_{pr} \simeq 6 \times 10^{34} \text{ G} \cdot \text{cm}^3 \times I_{45}^{1/2} m^{5/12} v_7^{3/4} \left( \frac{\tau_{pr}^{(sp)}}{2000 \text{ yr}} \right)^{-1/2} \left( \frac{P_{pr}^{(sp)}}{6.7 \text{ hr}} \right)^{7/12}. \quad (6)$$

The magnetic field strength on the stellar surface in this case is in excess of  $10^{17}$  G, and the star is spinning down at the rate exceeding the value reported in [20] by seven orders of magnitude. This finding rules out a possibility for the neutron star in 1E 1613 to be in the propeller state.

Above mentioned discrepancies force us to conclude that the neutron star in 1E 1613 is currently in the accretor state. In this case its X-ray emission can be described in terms of matter infall at the rate

$$\dot{\mathfrak{M}}_0 \simeq 5 \times 10^{13} \text{ m}^{-1} R_6 L_{34} \text{ g/s} \quad (7)$$

onto the surface of a neutron star with magnetosphere radius

$$r_{\text{mag}} \simeq 3 \times 10^8 R_6^3 \left( \frac{a_p}{600 \text{ m}} \right)^{-2} \text{ cm}. \quad (8)$$

Here  $L_{34}$  is the average X-ray luminosity of the pulsar in units of  $10^{34}$  erg/s,  $R_6$  is the neutron star radius,  $R_{\text{ns}}$ , in units  $10^6$  cm, and  $a_p \approx R_{\text{ns}} (R_{\text{ns}}/r_{\text{mag}})^{1/2}$  is the average radius of the hot spots at the base of the accretion column estimated in [15] through the X-ray spectrum of the source.

The lack of observational evidence for the binary nature of the object suggests that the only possible source of matter to be accreted by the neutron star is a fossil disk formed after the supernova explosion. Analyzing such situation in the previous paper, [21], we have shown that steady rotation of the star ( $|\dot{\nu}| \leq 2.8 \times 10^{-18}$  Hz/s) with the period of 6.7 hr can be explained assuming that either the angular velocity of matter in the residual disk is significantly smaller than the Keplerian velocity, or magnetic field on the stellar surface is in excess of  $\sim 10^{16}$  G. The magnetosphere radius of the star in this case turns out to exceed by a factor of 1000 the value  $r_{\text{mag}}$ , derived from observations.

The best agreement with observational data can be obtained in the model of magnetic-levitation accretion from a non-Keplerian magnetic residual disk in which the matter is confined by its own magnetic field [2, 30]. The outer radius of this disk is determined by the Shvartsman radius [31],

$$R_{\text{sh}} = \beta_0^{-2/3} r_G \left( \frac{c_s(r_G)}{v_{\text{rel}}} \right)^{4/3}, \quad (9)$$

at which the magnetic pressure in the initially quasi-spherical flow reaches the value of its ram pressure. Here  $\beta_0$  is the ratio of the thermal,  $\rho c_s^2$ , to magnetic,  $B_f^2/8\pi$ , pressure in the material captured by the neutron star at its Bondi radius,  $r_G = 2GM_{\text{ns}}/v_{\text{rel}}^2$ , and parameters  $\rho$ ,  $B_f$  and  $c_s$  denote the density, magnetic field strength and the speed of sound in the accretion flow, respectively. At the Shvartsman radius the quasi-spherical flow is decelerated by its own magnetic field and transforms into a slowly rotating magnetically-levitating disk (ML-disk) [32, 33].

The inner radius of the ML-disk is expressed as [34]

$$r_{\text{ma}} \simeq 3 \times 10^8 \times \alpha_{0.1}^{2/13} \mu_{30}^{6/13} m^{5/13} T_6^{-2/13} \dot{\mathfrak{M}}_{14}^{-4/13} \text{ cm}, \quad (10)$$

where  $\alpha_{0.1} = \alpha/0.1$  is the ratio of the effective coefficient of the accretion flow diffusion into the magnetic field of the star at its magnetosphere boundary,  $D_{\text{eff}}$ , to the Bohm

diffusion coefficient normalized following the results presented in [35].  $T_6$  is the plasma temperature at the magnetosphere boundary in units of  $10^6$  K, and  $\dot{\mathcal{M}}_{14}$  is the mass accretion rate onto the stellar surface in units of  $10^{14}$  g/s. The radius  $r_{\text{ma}}$  corresponds to the radius of pulsar magnetosphere derived from observations if the magnetic field strength on the neutron star surface is  $B_* \sim 10^{12}$  G.

The torque applied to the star from the ML-disk [21, 34],

$$K_{\text{sl}} = \frac{k_t \mu^2}{(r_{\text{ma}} r_{\text{cor}})^{3/2}} \left( 1 - \frac{\Omega_0}{\omega_s} \right), \quad (11)$$

strongly depends on the angular velocity of matter at its inner radius,  $\Omega_0$ . Limitation of the rate of period changes obtained from observations [20], can be achieved in this case under condition  $\Omega_0 \sim \omega_s$ . Moreover, using the Eq. (11) we find that the characteristic spin-down time-scale in the previous epoch (i.e. when  $\Omega_0 \ll \omega_s$ ),

$$\tau_a \simeq \frac{P_s}{2\dot{P}_{\text{sl}}} = \frac{I(GM_{\text{ns}})^{1/2} r_{\text{ma}}^{3/2}}{2\mu^2}, \quad (12)$$

for parameters of 1E 1613 is [21]

$$\tau_a \simeq 1880 \mu_{30}^{-17/13} m^{8/13} I_{45} T_6^{3/13} \dot{\mathcal{M}}_{14}^{-6/13} \text{ yr}, \quad (13)$$

and, correspondingly, does not exceed the age of the supernova remnant RCW 103 [12]. This result opens an opportunity to explain this exotic object without the assumption about a super-strong magnetic field of the neutron star to be invoked. In particular, we can envisage a situation, in which during the last 2000 years, the neutron star has been in the state of accretion from a slowly rotating,  $\Omega_0 \sim \omega_s$ , residual ML-disk with initial mass  $M_d$ , which was sufficient to maintain the process of accretion at the average rate  $\dot{\mathcal{M}}_0 \sim 10^{14}$  g/s over a time interval of  $\tau_0 \sim 2000$  yr, i.e.  $M_d \geq M_0$ , where

$$M_0 = \dot{\mathcal{M}}_0 \tau_0 \simeq 3 \times 10^{-9} M_{\odot}. \quad (14)$$

Analysis of this scenario leads us to the necessity to answer the following two questions: i) when and why a massive residual disk was formed around the neutron star, and ii) why the neutron star switched to the accretor state immediately after the supernova explosion which had given birth to the nebulosity RCW 103. It is very difficult to answer the second question in the frame of evolutionary scenario for an isolated neutron star since it requires assumption that the spin period of the neutron star at the moment of its birth was in excess of a critical value (see Eq. 22 in [21])

$$P_{\text{ma}} \simeq 3.5 \text{ s} \times \mu_{30}^{9/13} m^{-5/13} T_6^{-3/13} \dot{\mathcal{M}}_{14}^{-6/13}, \quad (15)$$

at which the equality  $r_{\text{ma}} = r_{\text{cor}}$  is valid. However, we cannot exclude a possibility that the pulsar 1E 1613 is a descendant of a HMXB and was born long before the explosion of its massive companion resulted in formation of supernova remnant RCW 103. Discussing this possibility in the next Section, we show that by the moment of the second

supernova explosion the spin period of the old neutron star could significantly exceed the value  $P_{\text{ma}}$  and the mass of disk surrounding its magnetosphere under certain conditions could be comparable or even exceed  $M_0$ . Accreting from a residual disk, the star will manifest itself as an X-ray pulsar even after the disruption of a binary system on a time span of at least a few thousand years.

## 4. FORMATION OF AN ISOLATED PULSAR DUE TO BINARY DISRUPTION

We consider a situation in which 1E 1613 is a neutron star which was born in a close massive binary system in the first supernova explosion. We assume that the system was not disintegrated and a neutron star formed a close pair with its massive companion. The initial spin period of the neutron star was of the order of fractions of a second and then steadily grew as the star had passed the ejector and propeller phases. Afterwards the star had switched to the accretor state, in which it remained until the second supernova explosion, caused by the core-collapse of its massive companion. This event was very likely to result in system disintegration [36], and the old neutron star became an isolated pulsar embedded in the supernova remnant of its companion and observed now in a form of nebulosity RCW 103.

### 4.1. Magneto-rotational evolution

By now, the above-described evolutionary scenario for a HMXB has been quite adequately studied and is considered as canonical by the majority of authors (see [37] and references therein). The life-time of such a system is limited by the evolutionary time of its optical component on the main sequence which for the star of mass  $M_{\text{opt}}$  is [38]

$$t_{\text{ms}} \simeq 6 \times 10^6 \left( \frac{M_{\text{opt}}}{20 M_{\odot}} \right)^{-5/2} \text{ yr.} \quad (16)$$

Numerical simulations of magneto-rotational evolution of a neutron star within this scenario with account for dissipation of its magnetic field were made by Urpin et al. [39]. According to their results, the stellar magnetic field decreases by an order of magnitude on the average due to diffusion and accretion screening [40] over a time interval  $t_{\text{ms}}$ . In particular, the initial surface magnetic field of the star  $\sim 10^{13}$  G will decrease down to  $\sim 10^{12}$  G in the course of its evolution as a member of a HMXB. Throughout most of its evolution, the star remains in the ejector state (see Eq. 17 from [41])

$$\tau_{\text{ej}} \sim 3 \times 10^6 \mu_{30.5}^{-1} I_{45} \dot{M}_{14}^{-1/2} v_7^{-1/2} \text{ yr.} \quad (17)$$

During this time its magnetic field drops by a factor of 3 (rapid cooling of the star during this phase significantly reduces the rate of magnetic field diffusion in its crust [39]).

As soon as the spin period of the star reaches its critical value (see Eq. 16 from [41]),

$$P_{\text{ej}} \sim 1.2 \text{ s} \times \mu_{30.5}^{1/2} \dot{M}_{14}^{-1/4} v_7^{-1/4}, \quad (18)$$

it switches to the propeller state in which the spin-down torque exerted on the star by the gas, penetrating inside its Bondi radius, is given by the expression  $K_{\text{sd}}^{(\text{pr})} \sim \mu^2/r_{\text{m}}^3$  [42, 26]. The duration of the propeller phase,

$$\tau_{\text{pr}} = \frac{\pi I r_{\text{m}}^3}{\mu^2 P_{\text{ej}}}, \quad (19)$$

strongly depends on the geometry and physical parameters of the accretion flow. This parameter takes the minimum possible value,

$$\tau_{\text{pr}}^{(\text{sl})} \simeq 6000 \text{ yr} \times \alpha_{0.1}^{6/13} \mu_{30}^{-29/26} I_{45} m^{3/13} T_6^{-6/13} \mathfrak{M}_{14}^{-35/52} v_7^{1/4}, \quad (20)$$

within the scenario of magnetic-levitation accretion, in which the star is surrounded by a non-Keplerian ML-disk and its magnetosphere radius is  $r_{\text{m}} = r_{\text{ma}}$ . Eq. (20) has been obtained by solving the system of equations (10), (18) and (19).

## 4.2. Parameters of a magnetically-levitating disk

Formation of a non-Keplerian magnetic disk in the Roche lobe of the neutron star which is a member of a HMXB can proceed if  $R_{\text{sh}} > \max\{r_{\text{A}}, r_{\text{circ}}\}$ , where  $r_{\text{circ}} = \xi^2 \Omega_{\text{orb}}^2 r_{\text{G}}^4 / GM_{\text{ns}}$  is the circularization radius, and  $\Omega_{\text{orb}} = 2\pi/P_{\text{orb}}$  is the angular velocity of the orbital motion with the period  $P_{\text{orb}}$ . This is valid if the neutron star velocity relative to the wind of its companion satisfies the inequality  $v_{\text{kd}} < v_{\text{rel}} < v_{\text{ma}}$ , where [21]

$$v_{\text{ma}} \simeq 380 \text{ km/s} \times \beta_0^{-1/5} m^{12/35} \mu_{30}^{-6/35} \mathfrak{M}_{14}^{3/35} c_6^{2/5} \quad (21)$$

and

$$v_{\text{kd}} \simeq 60 \text{ km/s} \times \xi_{0.2}^{3/7} \beta_0^{1/7} m^{3/7} c_6^{-2/7} \left( \frac{P_{\text{orb}}}{100 \text{ days}} \right)^{-3/7}. \quad (22)$$

Under these conditions, over a time span of  $\tau_{\text{ej}} + \tau_{\text{pr}}$ , the spin period of a neutron star reaches a critical value (see Eq. 22 from [21]),

$$P_{\text{pr}} \simeq 3.5 \text{ s} \times \mu_{30}^{9/13} m^{-5/13} T_6^{-3/13} \mathfrak{M}_{14}^{-6/13}, \quad (23)$$

at which the centrifugal barrier at the magnetosphere boundary fails to prevent accretion from a non-Keplerian ML-disk onto the stellar surface.

The mass of matter forming a ML-disk, surrounding the neutron star magnetosphere, can be expressed as follows:

$$M_{\text{d}} = 4\pi \int_{r_{\text{ma}}}^{R_{\text{sh}}} \rho(r) h_z(r) r dr, \quad (24)$$

where  $\rho(r)$  and  $h_z(r)$  are the density of matter in the disk and its half-thickness. These parameters can be evaluated taking into account that the gaseous (as well as magnetic)



pressure in the disk reaches the maximum value,

$$\rho(r_{\text{ma}})c_s^2(r_{\text{ma}}) = \frac{\mu^2}{2\pi r_{\text{ma}}^6}, \quad (25)$$

at its inner radius, corresponding to the magnetosphere radius of the star,  $r_{\text{ma}}$ , and decreases with distance from the magnetosphere boundary as  $\rho(r)c_s^2(r) \propto r^{-5/2}$  [32, 33]. Given that the gas temperature in the disk is

$$T(r) = \left( \frac{\dot{\mathcal{M}} GM_{\text{ns}}}{4\pi r^3 \sigma_{\text{SB}}} \right)^{1/4}, \quad (26)$$

and, correspondingly, the sound speed is  $c_s \sim (k_B T / m_p)^{1/2} \propto r^{-3/8}$ , the density of matter in the disk can be estimated as follows

$$\rho(r) = \rho(r_{\text{ma}}) \left( \frac{r}{r_{\text{ma}}} \right)^{-7/4}, \quad (27)$$

where  $\sigma_{\text{SB}}$  is the Stefan-Boltzmann constant,  $k_B$  is the Boltzmann constant and  $m_p$  is the proton mass.

The half-thickness of the disk can be expressed as [32, 33]

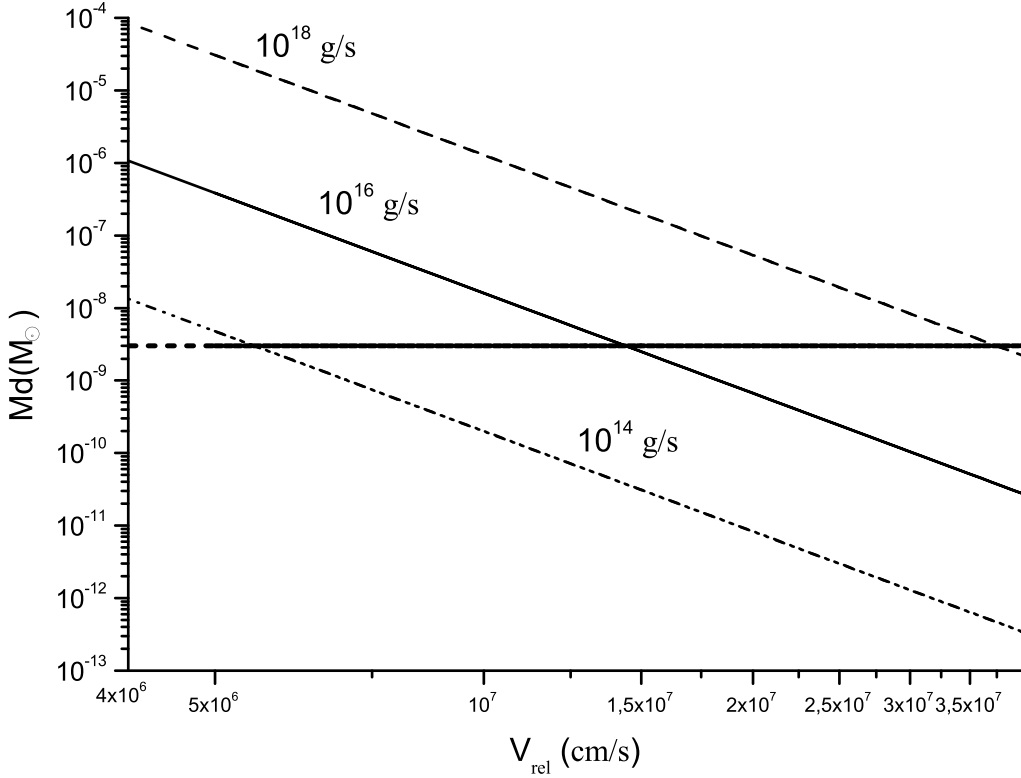
$$h_z(r) = \left( \frac{k_B T(r) r^3}{m_p GM_{\text{ns}}} \right)^{1/2}. \quad (28)$$

Substituting (9) and (26–28) into (24) and bearing in mind that under the conditions of interest  $R_{\text{sh}} \gg r_{\text{ma}}$ , we find

$$M_d \simeq 2 \times 10^{-10} M_{\odot} \times \alpha_{0.1}^{-7/3} \beta_0^{-11/12} \mu_{30}^{5/13} \dot{\mathcal{M}}_{14}^{99/104} m^{25/52} c_6^{11/6} v_7^{-55/12}. \quad (29)$$

Analyzing the function  $M_d = M_d(v_{\text{rel}})$ , presented in the figure 1 for different values of  $\dot{\mathcal{M}}$ , we find that a residual disk can be formed only in the wide systems with slow stellar wind in which  $v_{\text{rel}} \sim 100$  km/s. Such situation can be realized in the systems where a massive component is either Oe/Be star with outflowing disk or a red giant. In this case the value of  $v_{\text{rel}}$  is comparable to the orbital velocity of the neutron star. The mass of residual disk also substantially depends on the mass exchange rate between the system components at the end of the system evolution. In particular, for the most plausible values of  $v_{\text{rel}} \sim 100 - 200$  km/s (the orbital velocity of the neutron star in a HMXB with the orbital period of 100 – 200 days), the mass of a disk surrounding 1E 1613 exceeds  $M_0$  if during the previous epoch, the neutron star was in the state of accretion from a magnetized stellar wind with the rate  $\dot{\mathcal{M}} \geq 10^{15} - 10^{16}$  g/s. As has been recently shown in [34], the angular velocity of matter in the magnetic disk can be evaluated using the expression (see also [43])

$$\omega_{\text{sl}} \sim \frac{2\pi}{P_{\text{orb}}} \left( \frac{r_G}{R_{\text{sh}}} \right)^2, \quad (30)$$



**FIGURE 1.** Dependence of the mass of a residual ML-disk,  $M_d$ , on the relative velocity of a neutron star,  $v_{\text{rel}}$ , capturing material from the magnetized stellar wind in a high-mass X-ray binary, for different values of the mass exchange rate,  $\dot{M}$ , and the sound speed value in the wind  $c_s(r_G) = 10 \text{ km/s}$ . Horizontal line indicates the mass of a residual disk  $M_0 = 3 \times 10^{-9} M_\odot$ , necessary to maintain the process of accretion in the isolated pulsar 1E 1613 at the average rate of  $10^{14} \text{ g/s}$  over a time span of 2000 years.

which assumes that inside the region  $R_{\text{sh}} \leq r \leq r_G$ , accretion proceeds in a quasi-spherical regime with conservation of the angular momentum, while a magnetic disk, in which the movement of material is controlled by the intrinsic magnetic field of the flow, is in solid-body rotation. The condition  $\omega_{\text{sl}} \sim \omega_s$  in this case is satisfied if  $c_s(r_G) \sim \beta_0^{-2/3} v_{\text{rel}} (P_*/P_{\text{orb}})^{3/8}$ . Adopting the sound speed in a magnetized ( $\beta_0 \sim 1$ ) stellar wind in the neutron star vicinity to be  $\sim 10 \text{ km/s}$ , we find that the angular velocity of the magnetic disk is comparable to that of a neutron star in the present epoch provided the orbital period of a binary system at the final stage of its evolution was in the range 100 – 200 days.

## 5. CONCLUSIONS

The basic conclusion of our research is that the origin of an isolated X-ray pulsar with the period of 6.7 hr can be explained in terms of canonical evolutionary scenario for a High-Mass X-ray Binary without an assumption about the super-strong magnetic field on the neutron star surface. Our approach is consistent with common belief about a relatively short initial spin period of neutron stars and does not invoke additional assumption about a fall-back accretion onto a neutron star after its birth. The age of 1E 1613 in our scenario is in excess of a few million years, and the fossil disk, surrounding the neutron star magnetosphere at the present time, was formed during its evolution as a member of a HMXB.

According to our scenario of the origin of an isolated X-ray pulsar, the neutron star turns out to be in the accretor state long before a supernova explosion caused by the core-collapse of its massive companion. As a result, the X-ray luminosity of such an object significantly exceeds its spin-down power,  $L_{\text{sd}} = I\omega_s\dot{\omega}$ , that can be used as one of identification criteria for this class of objects. The period of such a pulsar substantially depends on the parameters of a binary system, magnetic field strength on the neutron star surface and mass exchange rate between the system components. However, in all circumstances its value is limited as  $P_s \geq P_{\text{ma}}$ . Isolated pulsars with anomalously long periods are likely to be the descendants of the widest pairs, in which the massive component underfills its Roche lobe at the end of its evolution and the mass exchange between the components occurs via a wind-fed accretion up to the moment of system disruption. The life-time of such a pulsar is determined by both the mass of residual disk and physical parameters in the gas defining the rate of magnetic field diffusion. For the parameters of interest the dominant mode is an ohmic diffusion with a characteristic time scale less than a few tens of thousands of years. In this light, the best candidates for descendants of the high-mass X-ray binaries are isolated X-ray pulsars associated with supernova remnants which were formed in the process of core-collapse of their massive companions. The objects of this type are known as Compact Central Objects (CCOs), 1E 1613 is a representative of this class of isolated neutron stars.

## ACKNOWLEDGMENTS

This work was partly supported by RFBR grant No 13-02-00077, SPbSU Grant No 6.38.669.2013 and the RAS Presidium Program No 21 “Non-stationary phenomena in the Universe”.

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